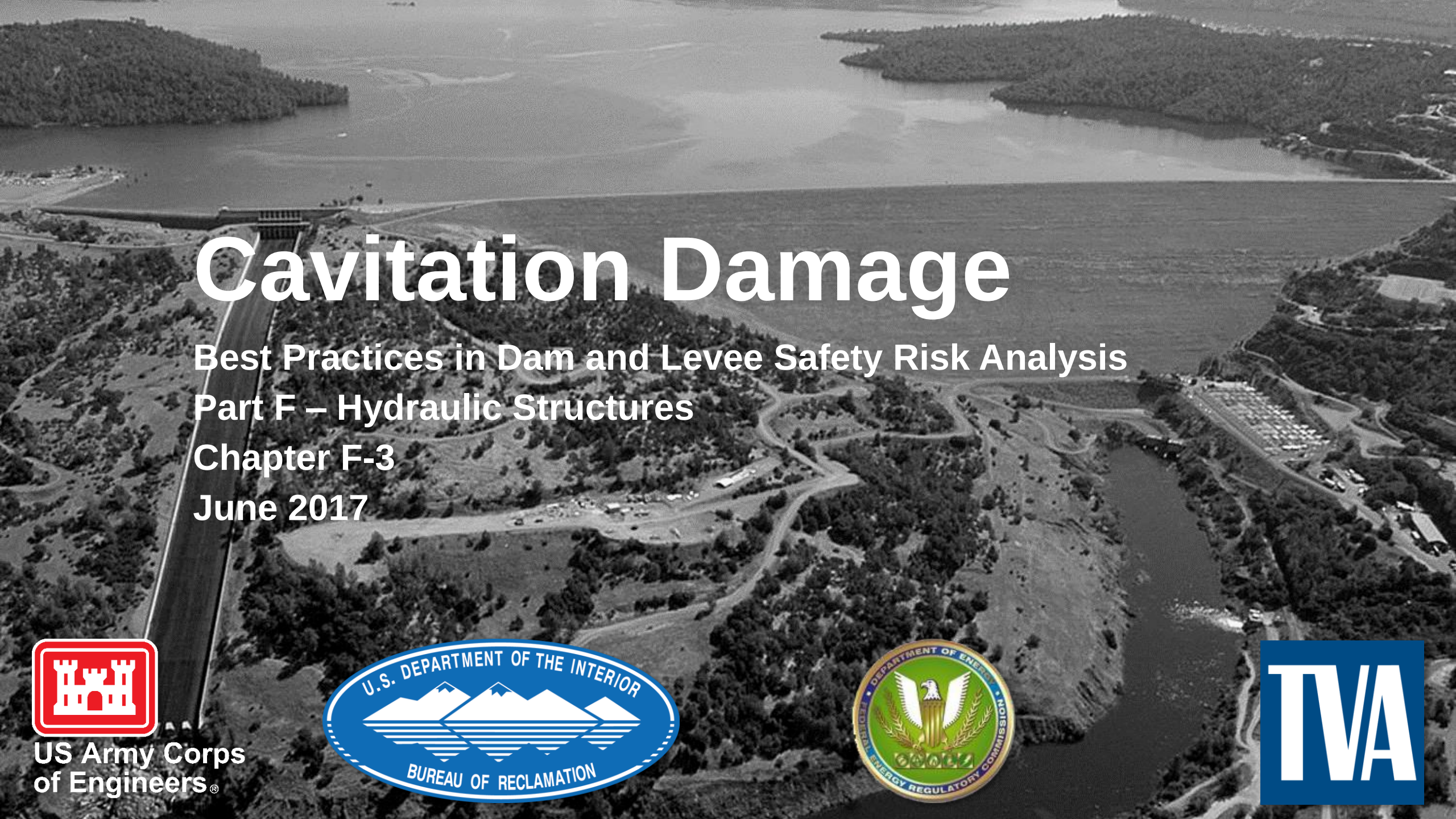


Cavitation Damage

Best Practices in Dam and Levee Safety Risk Analysis

Part F – Hydraulic Structures

Chapter F-3

June 2017

US Army Corps of Engineers®

U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION

DEPARTMENT OF ENERGY
FEDERAL ENERGY REGULATORY COMMISSION

TVA

Outline

- Cavitation Basics
- Case Histories
- Typical Event Trees
- Key Considerations
- Analytical Methods
- Defensive Measures

Objectives

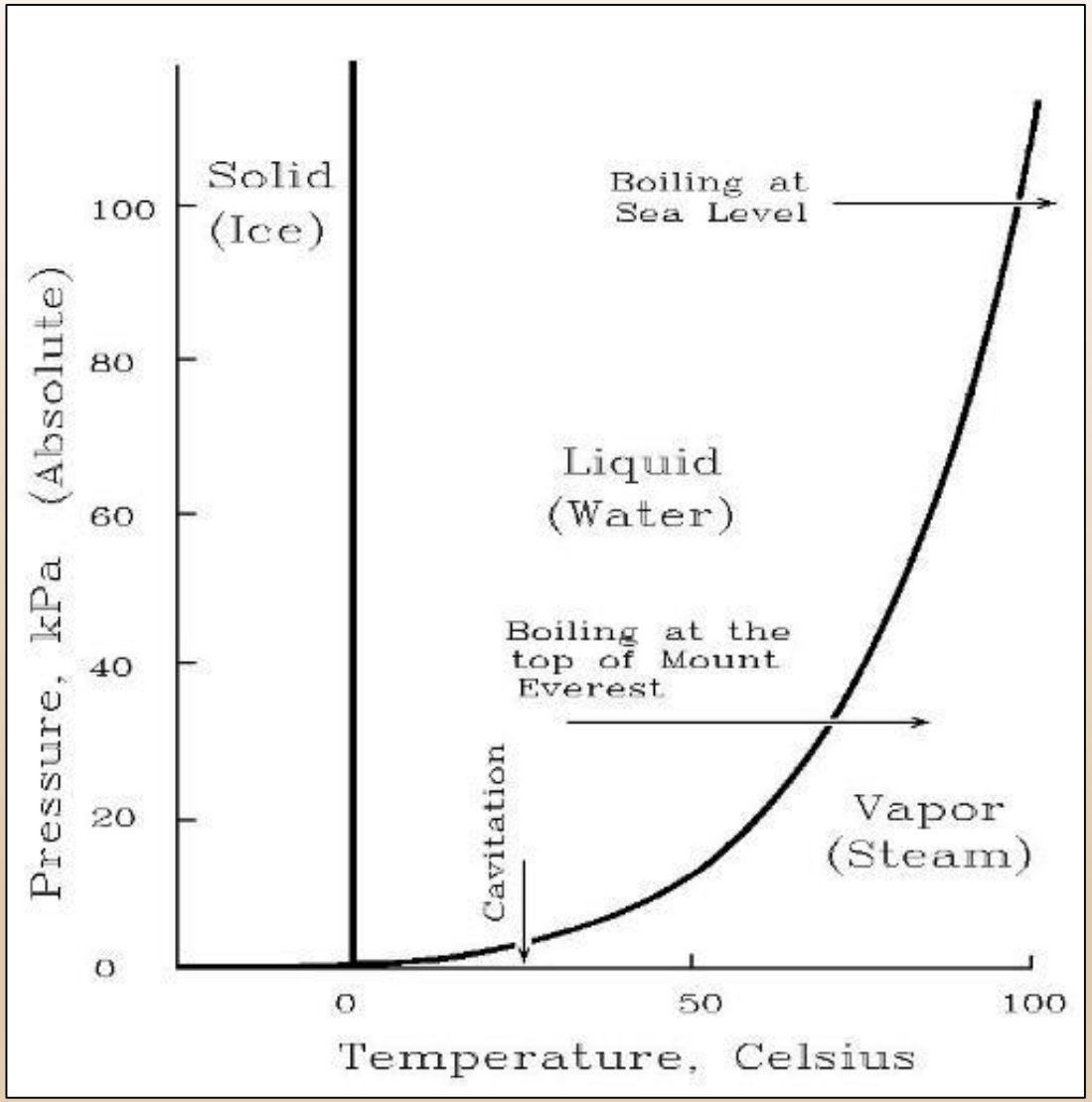
- Understand the mechanisms that cause Cavitation Damage
- Understand how to construct an event tree to evaluate the potential for major cavitation damage related failure
- Understand how to estimate potential for major cavitation damage and understand the progression mechanism to failure

Key Concepts

- Cavitation damage is a time dependent process
- Cavitation potential can be estimated by computing a cavitation index
- Cavitation damage potential is dependent on other factors including the air concentration in flow, the durability of materials, irregularities along the flow surface, and flow durations
- Cavitation damage has resulted in significant damage at several large federal dams

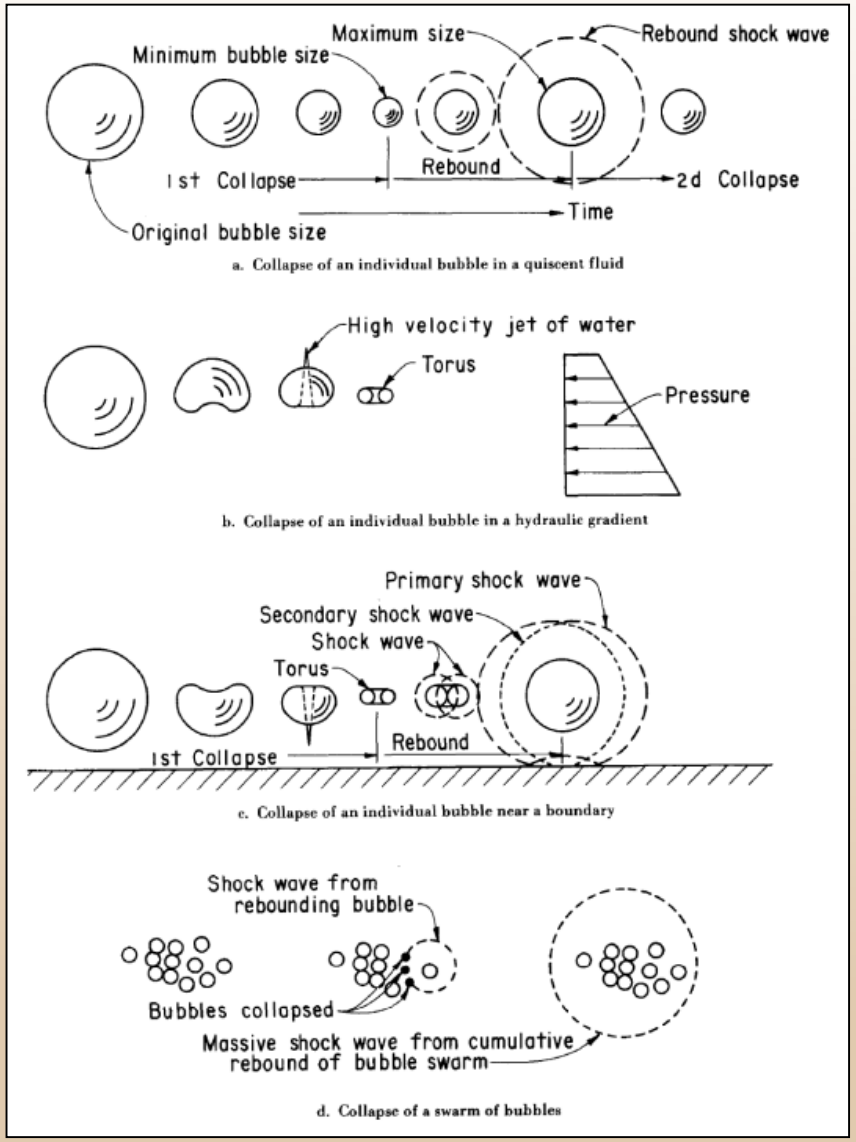
Cavitation Basics

Cavitation Basics



Cavitation Basics

- Cavitation occurs in high velocity flow, where water pressure is reduced locally because of an irregularity in the flow surface
- As vapor cavities move into a zone of higher pressure, they collapse, sending out high pressure shock waves
- If the cavities collapse near a flow boundary, there will be damage to the material at the boundary (cyclical loading induced fatigue failure - - - Long duration)



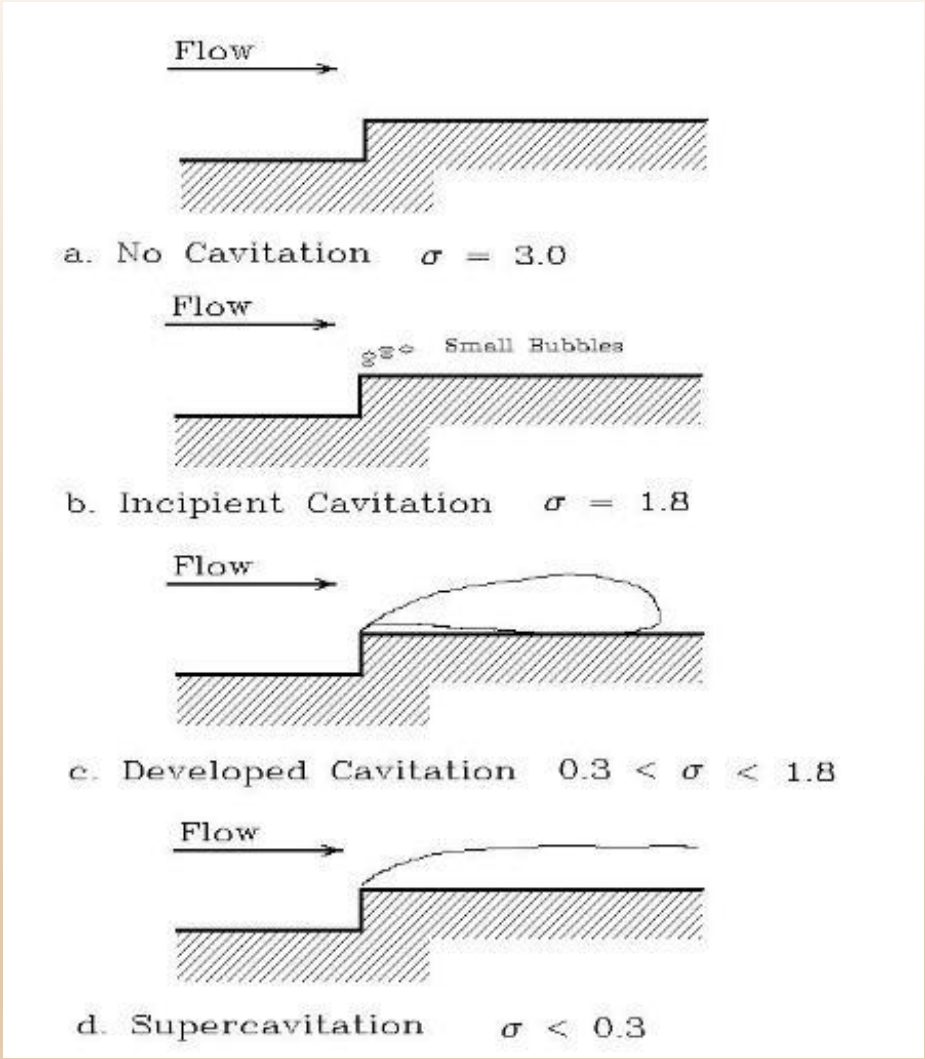
Cavitation Basics

Phases of Cavitation

- Incipient Cavitation – occasional cavitation bubbles form in flow; damage typically occurs for cavitation index values one-sixth to one-fourth of the incipient cavitation index for a given surface irregularity

- Developed Cavitation – many small cavitation bubbles are formed, appearing as a white fuzzy cloud

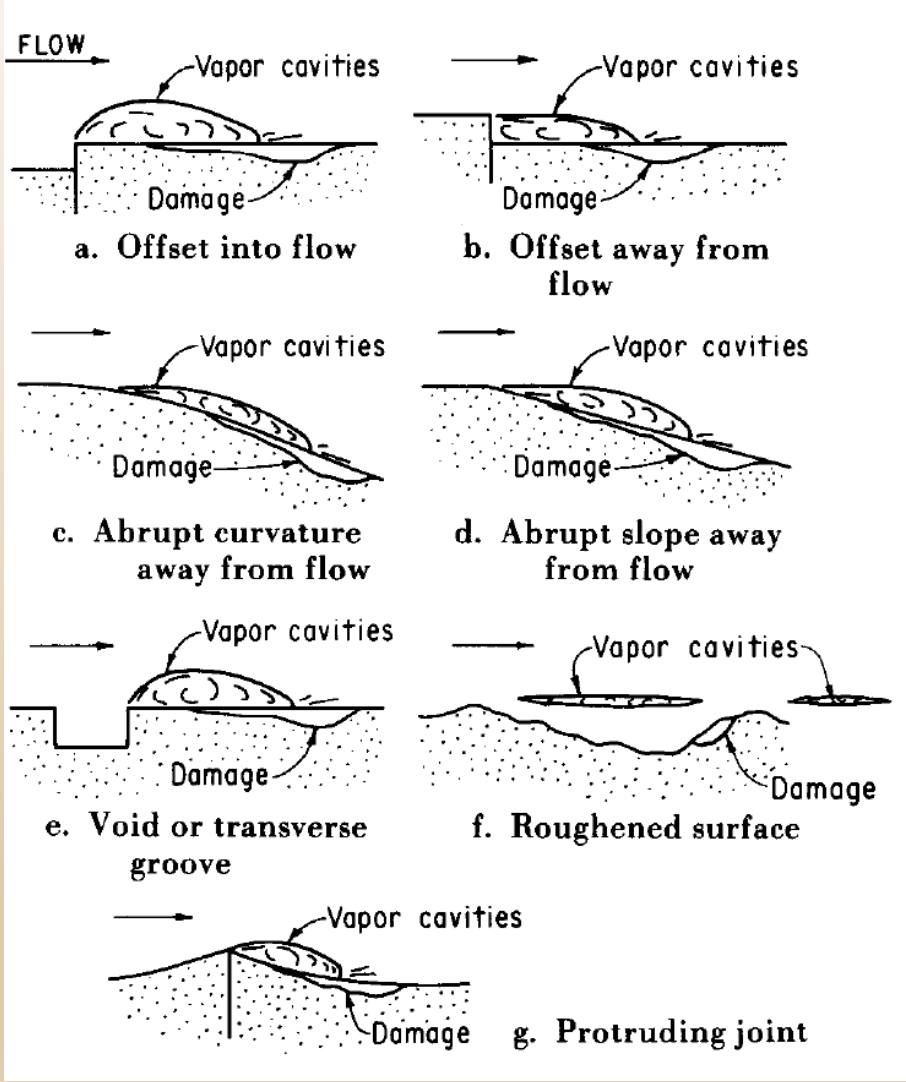
- Supercavitation – large vapor cavities are formed from individual cavitation bubbles



Cavitation Basics

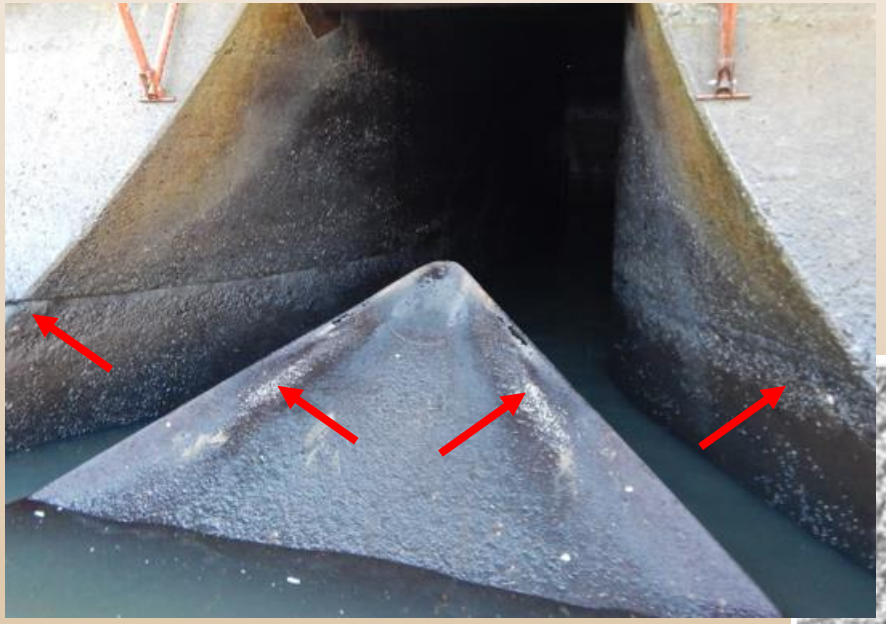
Cavitation Damage

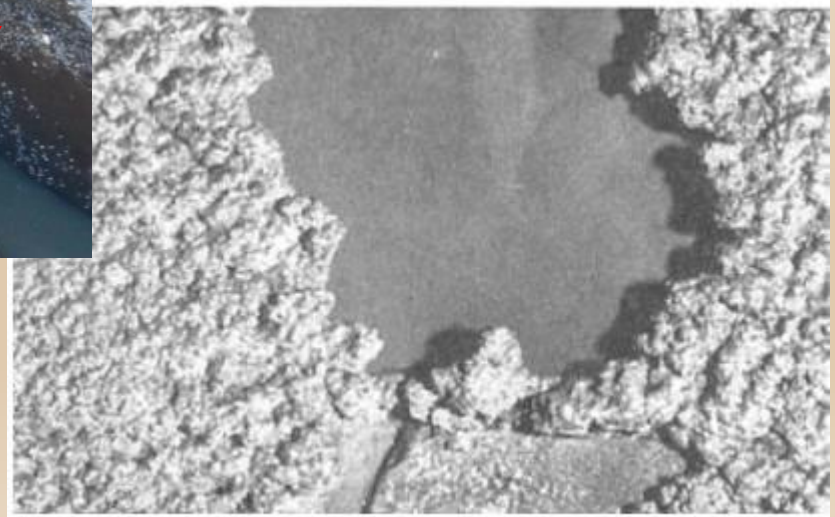
- Cavitation damage happens downstream from cavitation source (sudden change in pressure)
- Cavitation damage potential can be determined based on flow cavitation indices and the characteristics of flow surface irregularities
- Cavitaton damage is a time dependent process



Cavitation Basics

Spotting the Problem!



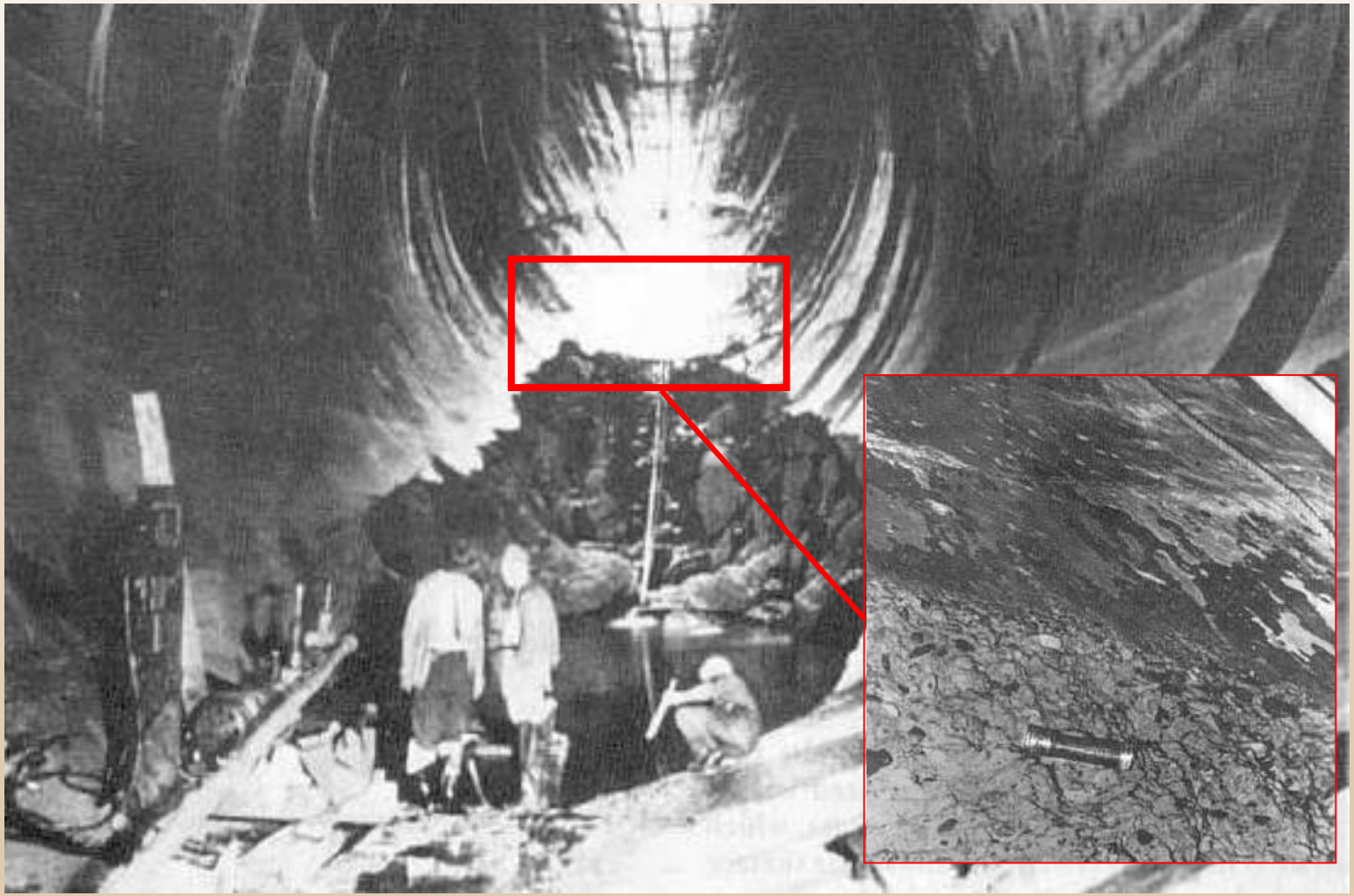


b. Ross Dam (Seattle, Washington) outlet works conduit

Case Histories

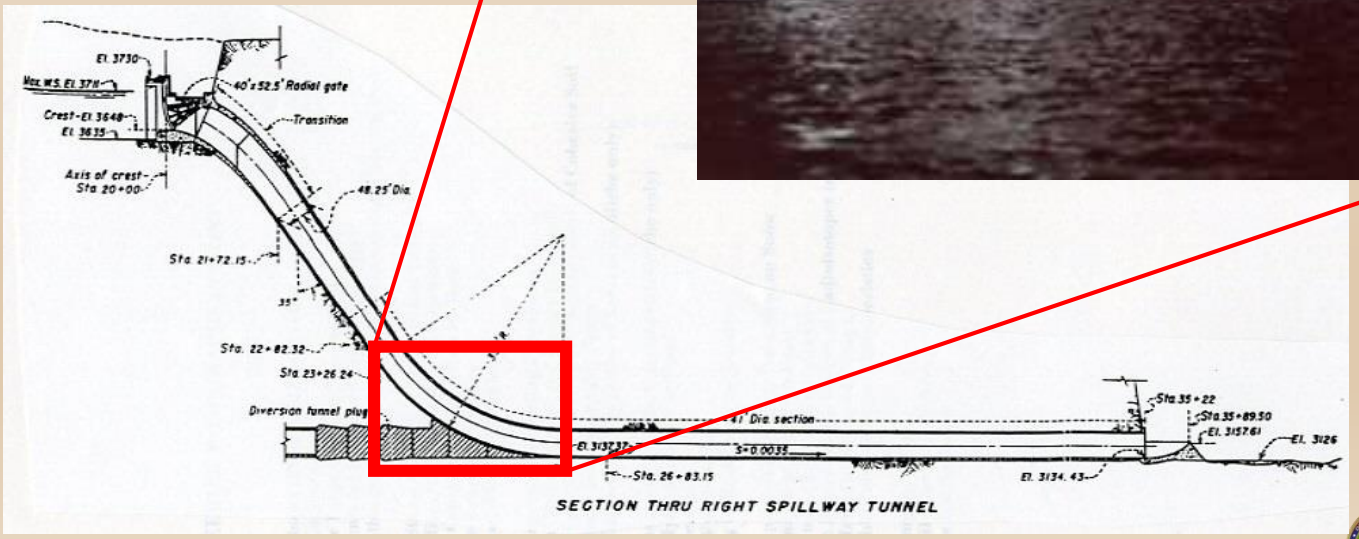
Hoover Dam Spillway

- Arizona spillway tunnel operated for 116 days in Winter of 1941
- Tunnel lining failed and eroded an exposed fault
- Damage was attributed to a misalignment of the tunnel invert



Glen Canyon Dam Spillway

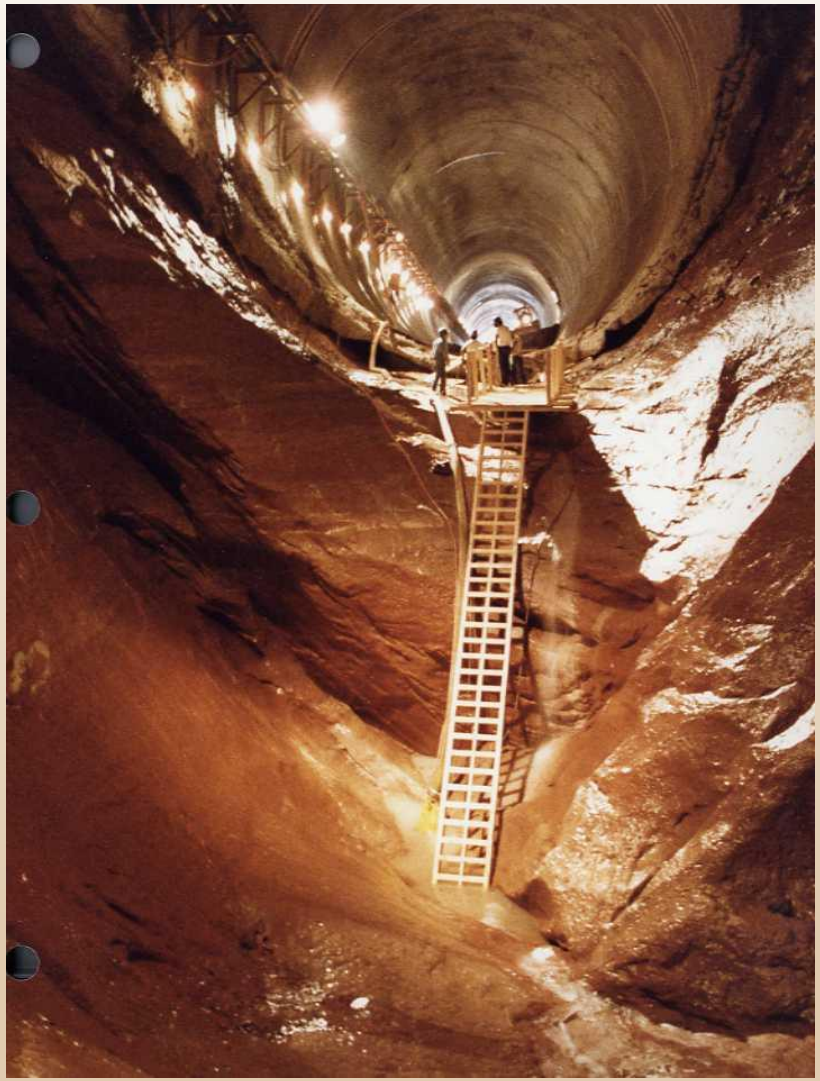
- 41-Foot-Dia. Tunnel with radial gates in each abutment.
- Combined discharge of spillways is 276,000 ft^3/s at reservoir water surface El. 3711
- Initial attempts to minimize releases (<6000 ft^3/s)
  - Right spillway ≈27,000 ft^3/s
  - Left spillway ≈ 32,000 ft^3/s
  - Outlets and power plant
    ≈ 44,000 ft^3/s
  - Duration exceeded 45 days



SECTION THRU RIGHT SPILLWAY TUNNEL

Glen Canyon Dam Spillway

- The cavitation damage was initiated by offsets formed by calcite deposits on the tunnel invert at the upstream end of the elbow
- Incipient cavitation indices of deposits along tunnel lining ranged from 0.64 to 0.73
- Cavitation indices of flow in areas where cavitation initiated in left tunnel spillway ranges from about 0.13 to 0.14 (1/4 to 1/6 range)
- Concrete lining repairs included the incorporation of air slots in both spillways



Left Spillway D/S of Elbow

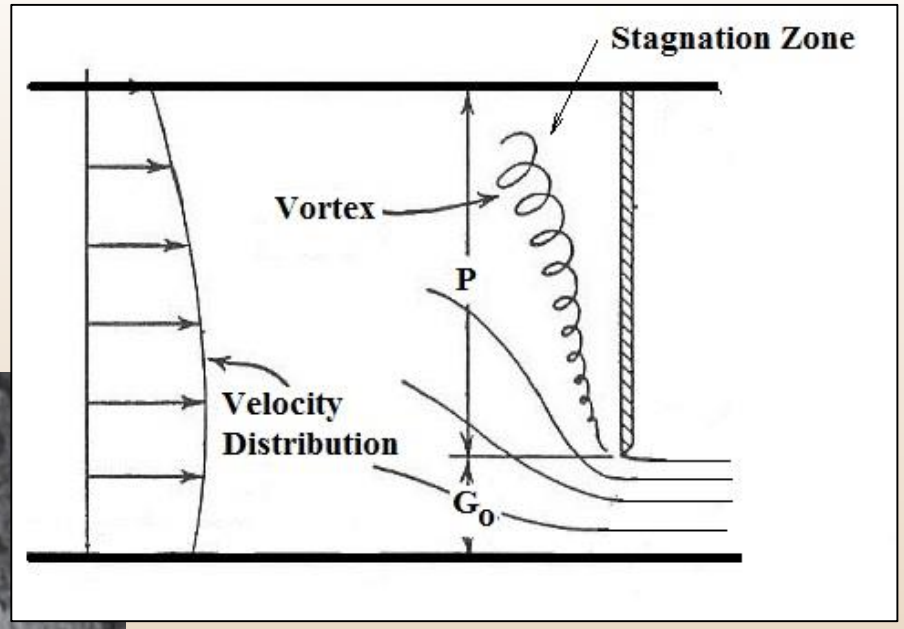
Libby Dam

- Sluice Outlets design head is 265-feet
- Severe Damage after 18 months of operation
- Majority of the damage was downstream of regulating gates
- Multiple other projects have experienced damage in this location

Libby/Palisades Dam

USBR – Palisades Dam

USACE – Libby Dam



Typical Event Tree

Typical Event Tree for Cavitation Damage

- Flows Conditions Exist to Create Cavitation
  - Cavitation Damage Initiates
    - Lining or Slab Fails
      - Head Cut Initiates
        - Unsuccessful Intervention
          - Head Cut Progresses to Breach

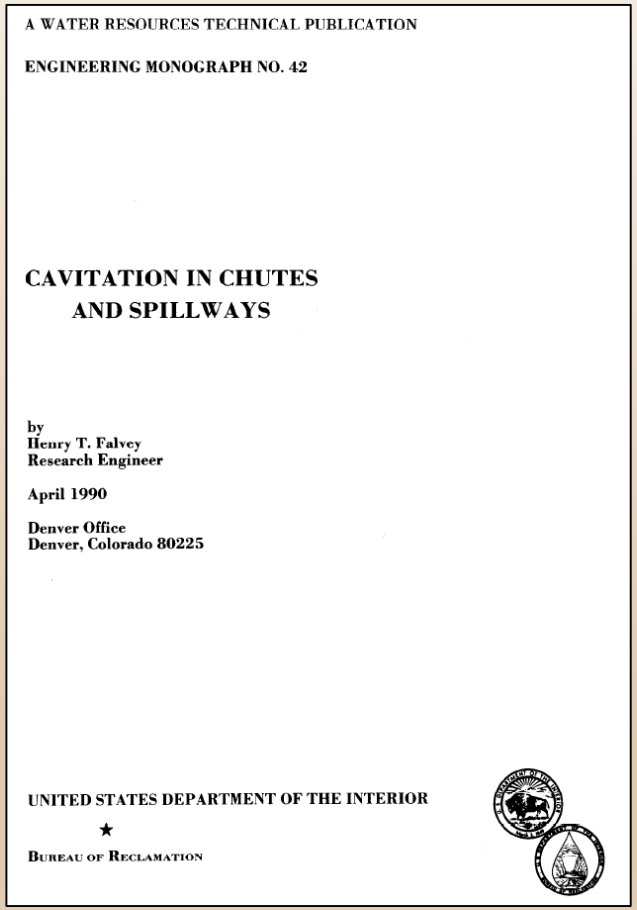
Key Considerations

Key Considerations

- Cavitation Indices (cavitation)
- Aeration of Flow (cavitation)
- Inspection Ability/Frequency
- Condition of Liner (usually concrete)
- Erodibility of Foundation Materials
- Duration and Frequency of Damaging Flows
- Ability to shut-off/decrease flow

Analytical Methods

Cavitation Damage



A WATER RESOURCES TECHNICAL PUBLICATION

ENGINEERING MONOGRAPH NO. 42

CAVITATION IN CHUTES
AND SPILLWAYS

by
Henry T. Falvey
Research Engineer

April 1990

Denver Office
Denver, Colorado 80225

UNITED STATES DEPARTMENT OF THE INTERIOR

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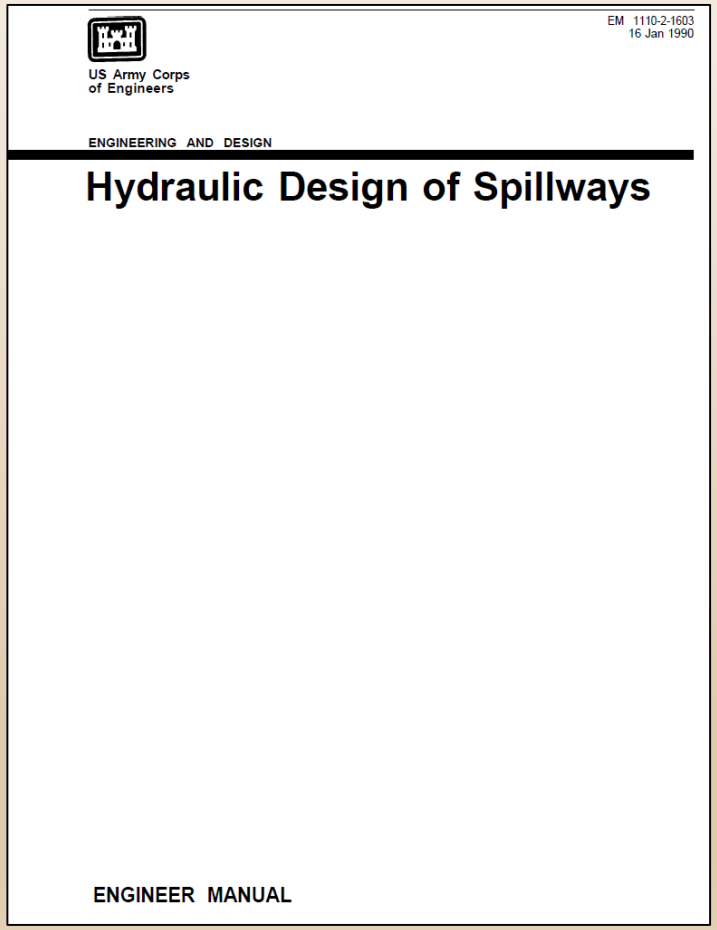
BUREAU OF RECLAMATION



EM 1110-2-1603
16 Jan 1990

US Army Corps
of Engineers

ENGINEERING AND DESIGN

Hydraulic Design of Spillways

ENGINEER MANUAL

Analytical Methods

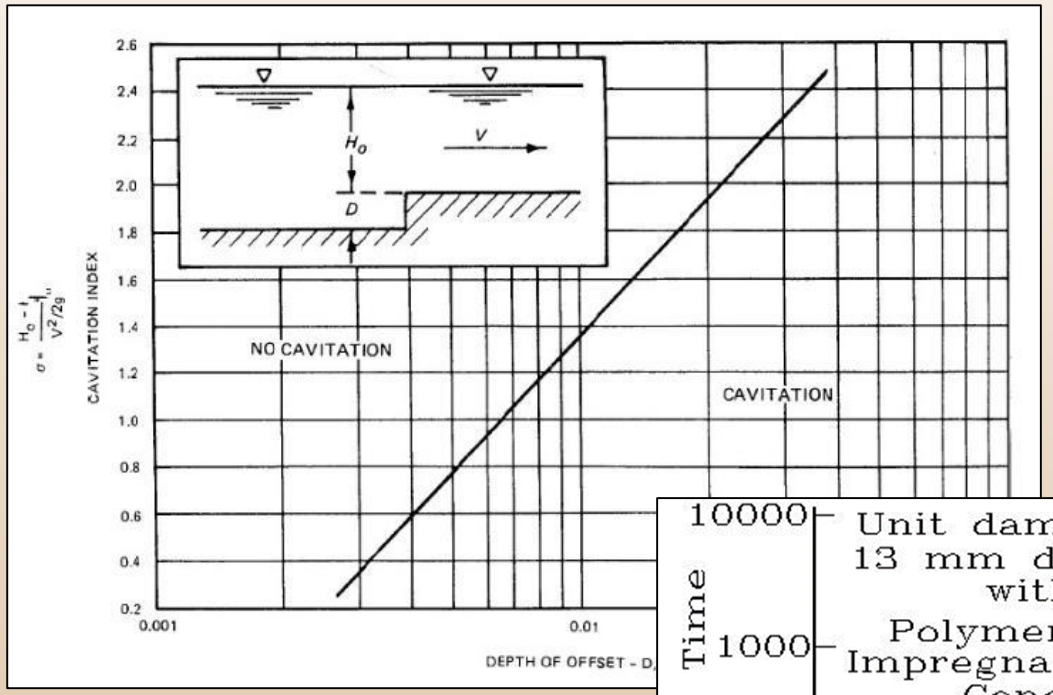
$$\sigma = \frac{P_o - P_v}{\rho \frac{V^2}{2}} = \frac{H_o - H_v}{\frac{V^2}{2g}}$$

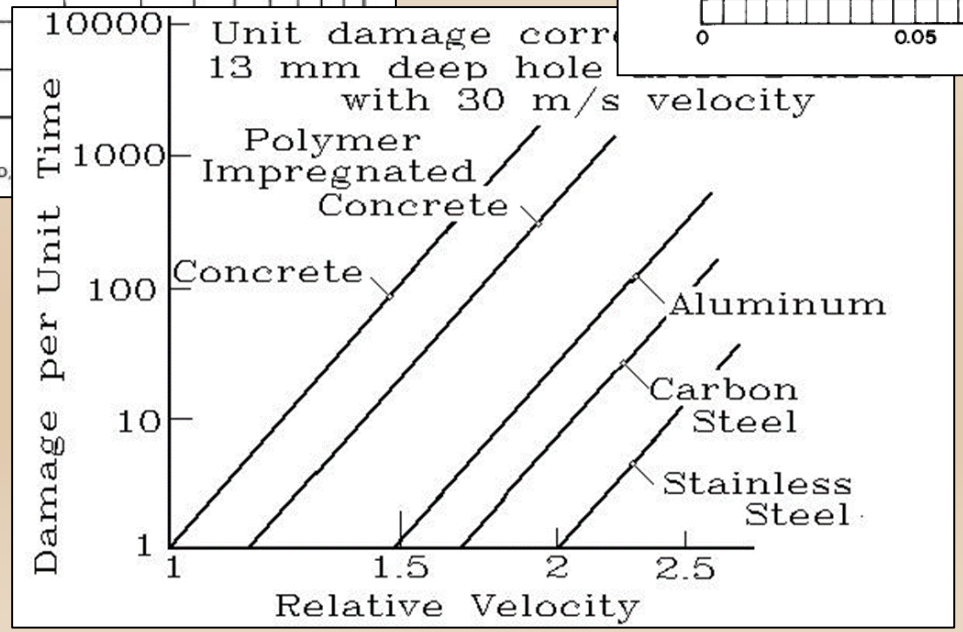
Where:

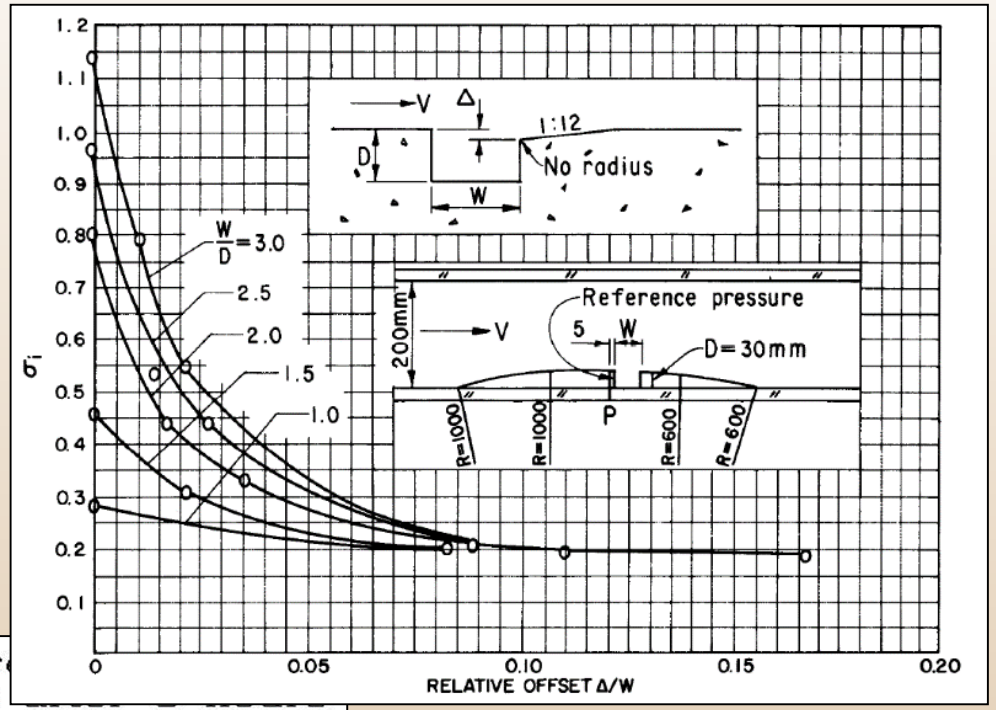
P_o = Reference Pressure
P_v = Vapor Pressure
V = Flow Velocity
ρ = Density

- Cavitation Indices can be used to evaluate the potential for cavitation damage in a spillway chute or tunnel
- There is the potential for cavitation damage when the cavitation index is between 0.2 and 0.5, for typical concrete
- For large features introduced into the flow abruptly (stilling basin baffle blocks or splitter walls) cavitation damage can occur for indices as high as 1.0 or greater

Analytical Methods







Cavitation Damage

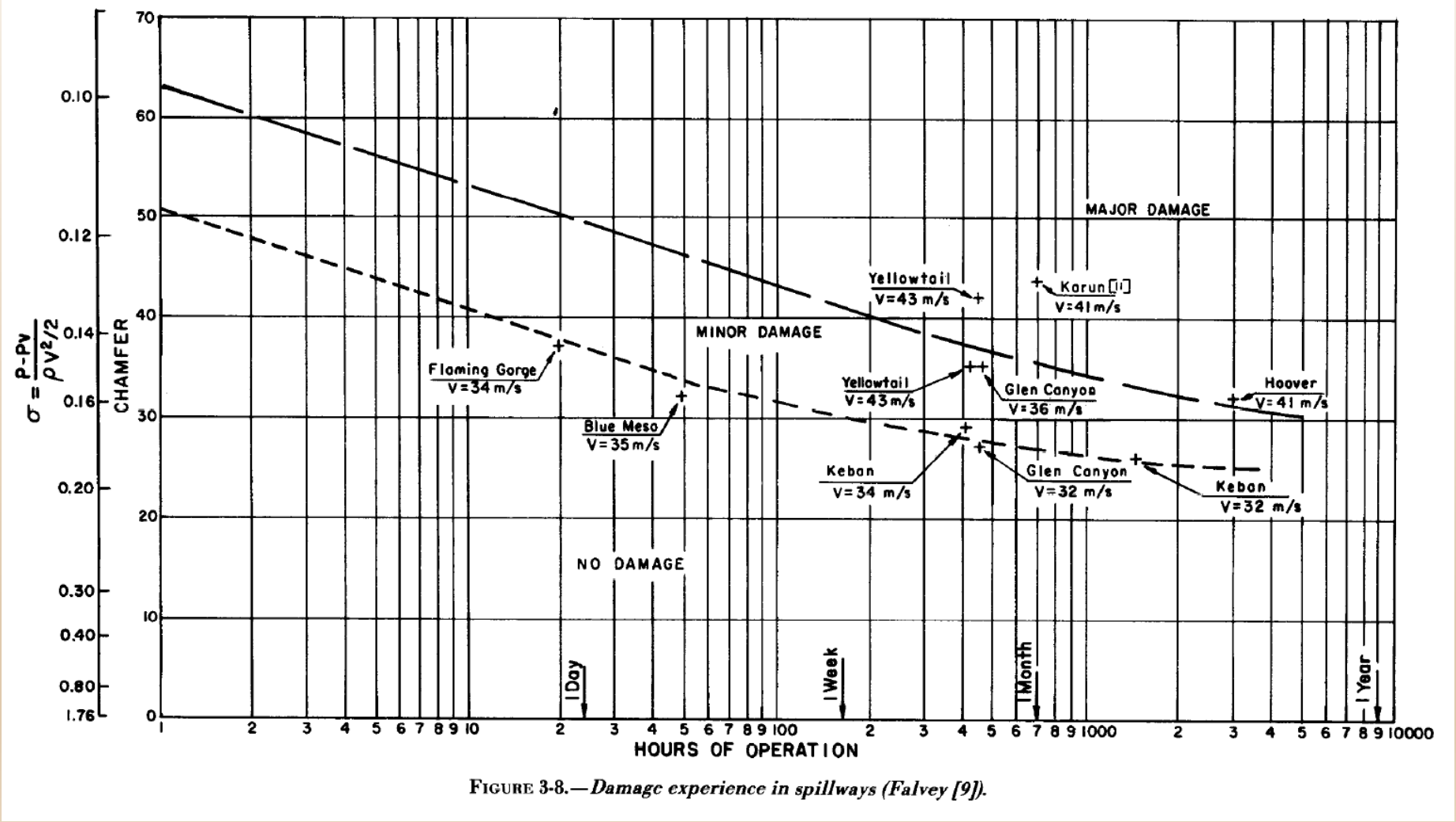


FIGURE 3-8.—*Damage experience in spillways (Falvey [9]).*

Cavitation Damage

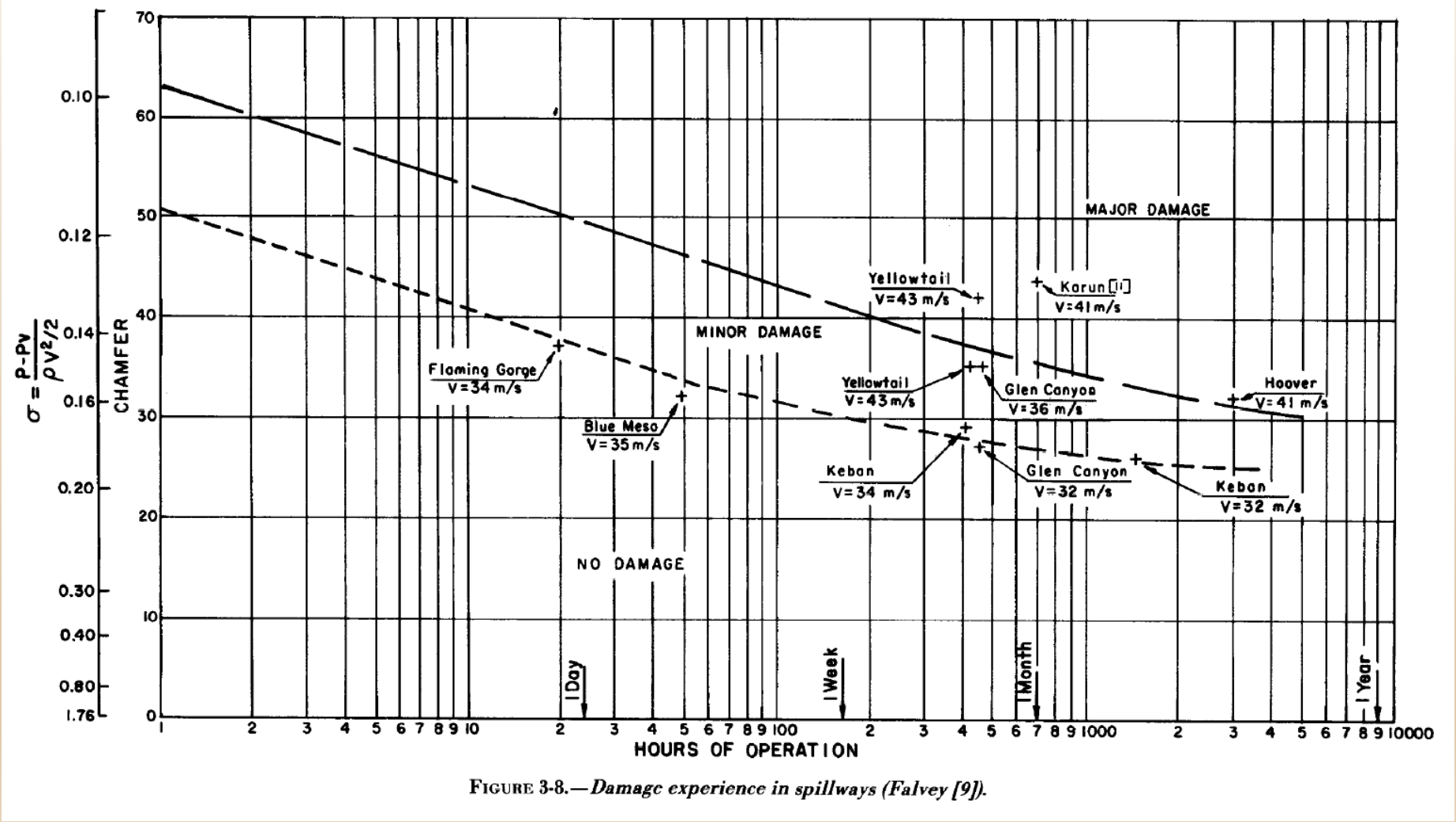
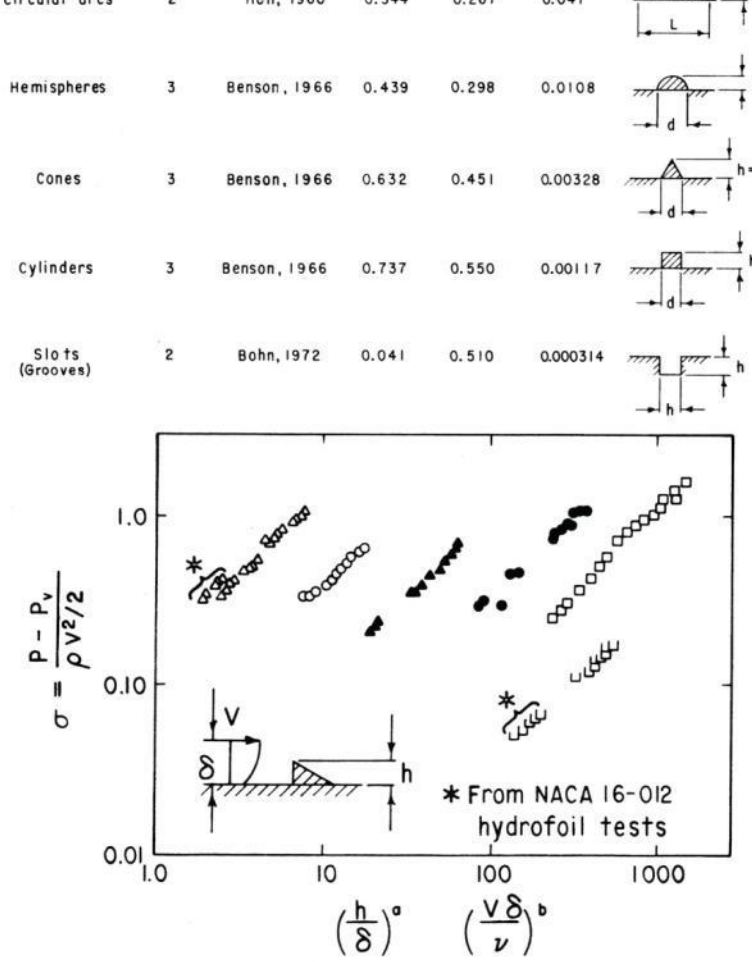


FIGURE 3-8.—*Damage experience in spillways (Falvey [9]).*

Incipient Cavitation from Singular Offsets

Symbol	Irregularity	Flow dimensions	Data source	a	b	C
△	Triangles	2	Holl, 1960	0.361	0.196	0.152
○	Circular arcs	2	Holl, 1960	0.344	0.267	0.041
▲	Hemispheres	3	Benson, 1966	0.439	0.298	0.0108
●	Cones	3	Benson, 1966	0.632	0.451	0.00328
■	Cylinders	3	Benson, 1966	0.737	0.550	0.00117
⊔	Slots (Grooves)	2	Bohn, 1972	0.041	0.510	0.000314

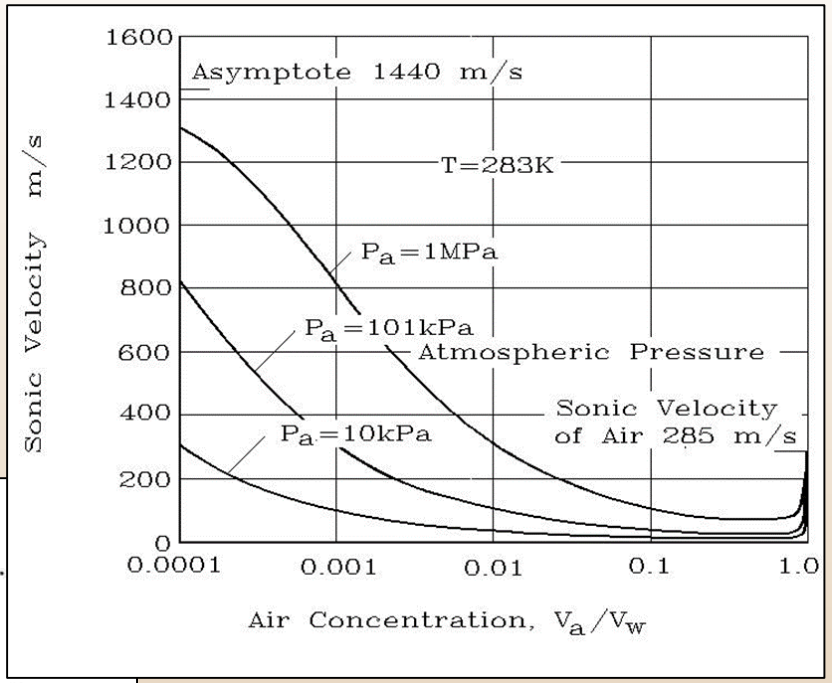


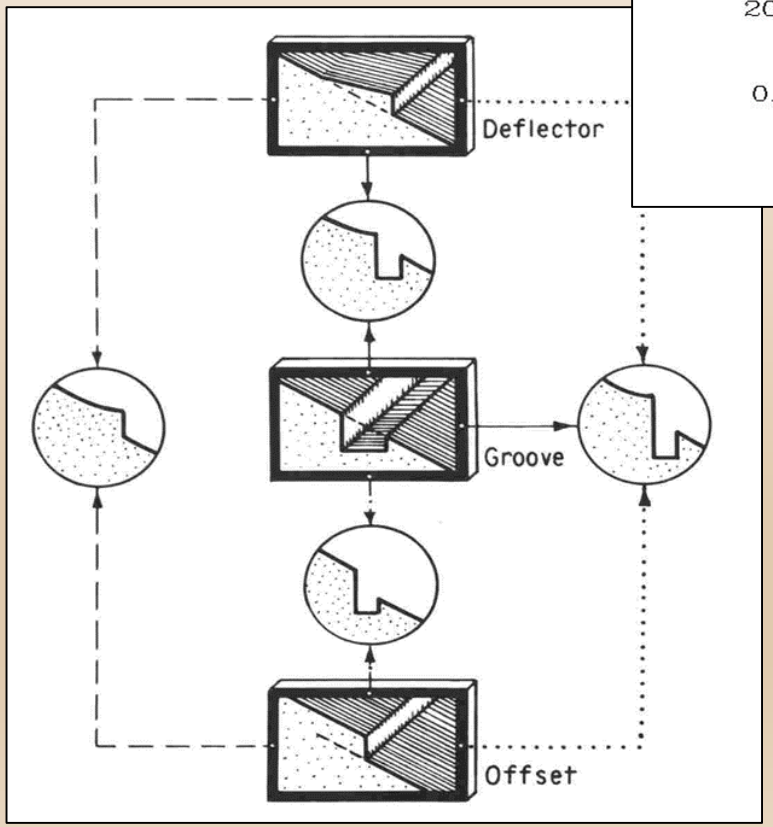
Defensive Measures

Defensive Methods

These items reduce the damage potential given a high cavitation potential is predicted

- Air Entrainment
- Polymerized Concrete
- Steel Liners
- Frequent Inspections and conduct repairs as necessary





Takeaway Points

- Cavitation is a time dependent process
- Cavitation damage has resulted in significant damage to spillways at large dams
- There are simple ways of estimating the relatively likelihood of developing major damage due to cavitation
- Cavitation damage is often part of the initiation of an event tree and often transitions into erosion of soil or rock


Questions
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